

# Use of Hydrophobic-Hydrophobic Interactions for Direct Graphene Transfer

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## Abstract

A new large-area wet transfer method to transfer graphene directly onto UHMWPE membranes without organic-coating, thermal treatment or other mediated substrate was developed. This method completely avoids the problems of PMMA-residue and possible PMMA coating induced tear-off by harnessing hydrophobic-hydrophobic interactions between graphene and UHMWPE, which is one of most facile and cheapest transfer methods that are currently available, especially for large-area graphene preparation and transfer. Multi-layer sandwich structure composite membrane of graphene and UHMWPE with desired number of layers can also be easily prepared by repeating the transfer method. The most significant applications of this transfer method lie on that it facilitates thin polymer membranes the possibilities to be directly observed with high magnification by electron microscopes, such as SEM and TEM. Thus the crystallization and phase-behavior of polymers including UHMWPE can be investigated with real-time and in-situ morphological observations, even in the presence of their solvent and with the need of thermal treatment. Morphologies and mechanical properties of

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stretched graphene/UHMWPE layered composite membranes were investigated, and strengthening effect of graphene on one side and both sides was observed.

*Key words:* graphene, transfer, UHMWPE, multi-layer sandwich structure, electron microscopy

## 1. Introduction

Graphene, the two-dimensional single atomic-thin layer of sp<sup>2</sup> carbon honeycomb lattice, has drawn enormous research interest due to its high carrier mobility,<sup>1</sup> mechanical strength and flexibility,<sup>2-4</sup> optical transparency<sup>5</sup> and extraordinary chemical resistance.<sup>6</sup> Since mechanical exfoliation has been developed to prepare mono-layer graphene in 2004,<sup>7</sup> a lot of effort has been spent to try out the methods to prepare high-quality large-area graphene and then get transferred effectively, among which the CVD-grown and subsequent PMMA-mediated transfer is the most widely used approach.<sup>8,9</sup> PMMA can be easily spin coated on graphene/copper film and grasps graphene by strong covalent bonding by baking, it can also be removed readily by acetone wash after transfer.<sup>10</sup> However later it is found using PMMA as support layer during transfer may degrade the quality and performance of prepared graphene mainly due to two reasons. Firstly PMMA coating may induce cracks and tears since it holds graphene rigidly and thus ripples between graphene and substrate retain, which later on causes the tear off of graphene during removal of PMMA by solvent wash.<sup>11</sup> Secondly owing to strong dipole interactions between PMMA and graphene, a thin layer of PMMA residue remains stuck on graphene after transferring.<sup>12</sup> And the p-doping effect on graphene of residue may cause carrier scattering, which results in a reduction of electrical and physical performance and carrier mobility.<sup>13,14</sup> Other approaches were reported to avoid or minimize the negative effects of PMMA-mediated transfer: to replace PMMA with other organic coating (PDMS,<sup>15</sup> PC<sup>12</sup>) or supporting layers and tapes,<sup>16-20</sup> to place substrates underneath graphene/copper during etching,<sup>21,22</sup> or to peel off graphene with adhesive layers.<sup>23,24</sup> While these alternatives are either too operationally complicated, or also possible to degrade performance of graphene by thermal

treatment and introducing adhesive substances.<sup>25</sup> To study intrinsic properties of graphene and to make them into electronic devices or separators, a clean while facile transfer approach after CVD growing is necessary and critical. In this paper, we present a new wet transfer method to directly transfer CVD-grown mono-layer graphene onto desired thin polymer membranes, by harnessing hydrophobic-hydrophobic interaction between graphene and polymer molecules. Hydrophobic-hydrophobic interaction, also termed as hydrophobic effect or hydrophobic force, is not actually a force, but the trend of two hydrophobic groups draw closer until vdW force become predominant by removing polar molecules out. The process is driven thermodynamically by the increase in enthalpy and sometimes also entropy (classical hydrophobic effect). Hydrophobic-hydrophobic interaction is commonly seen in nature, typical examples include assembly of phospholipids to form vesicles and the folding of proteins.<sup>26,27</sup> Thin polymer membrane holds graphene by vdW force throughout the whole transfer process, acting as both supporting layer during etching and targeted substrate after transfer, no extra organic coating nor removal involved. Graphene can thus fully spread on polymer membrane without cracks or tear-off, and the organic-mediate residue problem is also avoided completely.

In this work, the polymer membrane we used was ultra-thin UHMWPE biaxially oriented nano- porous membrane prepared in our lab, by gel-spinning and biaxial hot stretching. Prepared UHMWPE membranes is highly porous (volumetric porosity over 60%) and the average pore diameter is about 70 nm, with a tensile strength greater than 100 MPa. Interestingly, our UHMWPE membranes have graphene-like micro-structure, which are also multi-2D-layer stacking along thickness direction, connected by inter-layer fibrils (as shown in S1). Then the ultra-thin (1.1 micron) UHMWPE membranes were prepared by simple mechanical exfoliation (peeling off), a approach similar to the one used by Novoselov and Geim to prepare single layer graphene.<sup>7</sup> More detailed preparation procedure of UHMWPE membranes can be found in supporting information.

## 2. Experimental

For the new wet transfer approach, as demonstrated in Figure 1, firstly thin UHMWPE membrane was covered onto the top of CVD-grown graphene/copper film. At this step the distance between UHMWPE and graphene was far more than the effective range of vdW force, thus they two needed to be brought closer to each other. 96% ethanol was dripped on to swell UHMWPE membrane and then filled up the gap in-between UHMWPE and graphene (nano-porous UHMWPE membranes allow ethanol to permeate with high flux,  $195.4 \text{ L}/(\text{m}^2 \cdot \text{h})$  at 0.75 bar). Upon the hydrophobic-hydrophobic interaction between UHMWPE and graphene along with the drying of ethanol, surface tension of ethanol continuously pulled the two layers closer until vdW force became significant. Then the bottom copper layer was removed away by etching of  $\text{FeCl}_3$  solution, followed by HCl and DI water washing. Next the UHMWPE/graphene composite membrane was scooped by wafers or glass slides. Since UHMWPE is highly hydrophobic and low in density, it would be not be wet by water or aqueous solution and always floated on the solution surface throughout the transfer process, as shown in Figure 2C & D. As the water on composite membrane surfaces was dried out, the transfer of graphene onto UHMWPE membrane was completed. The whole transfer did not involve any organic coating and removing, compressing or thermal treatment.

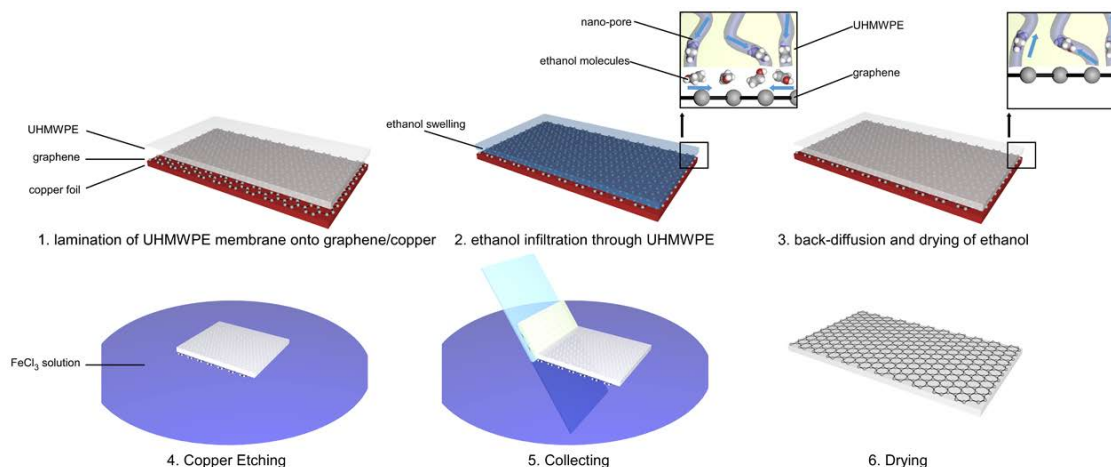


Figure 1: Schematic diagram illustrating the new direct wet transfer method to transfer CVD-grown mono-layer graphene onto UHMWPE membranes

### 3. Results and Discussions

Figure 2A & B demonstrate photographs of UHMWPE membrane before and after the transfer of graphene, the change in transparency due to graphene loading can be clearly seen. As shown in Figure S1 (ensure), UHMWPE membrane is highly porous and rough in surface featured with nano-pores. Transmittance of optical wave through membrane will be significantly reduced due to Mie scattering since the dimensions of particle or pore structure are comparable to light wavelength, especially at the interfaces.<sup>28,29</sup> By overlaying of graphene, rough surface of UHMWPE membrane is covered by smooth atomic thin graphene, and the effective vdW range is far less than optical light wavelength (0.157 nm),<sup>30</sup> a large proportion of Mie scattering on UHMWPE surface vanishes. Another issue concerning conventional PMMA-mediated method is that complete homogeneous covering of PMMA layer gets more and more tricky and costly when area of graphene to be transferred increases. CVD-grown graphene in our lab is typically 40 cm<sup>2</sup> large in area (as shown in Figure 2B), thus our direct wet transfer method is more necessary to make the transfer not only clean and smooth, but also operationally and economically preferable (UHMWPE is one of the cheapest engineering plastic materials).

To check the layer number and defects, Raman spectroscopy was characterized of graphene/copper film after CVD growing, and of graphene/UHMWPE composite membrane after transfer. 2D and G bands were at 2690 cm<sup>-1</sup> and 1596 cm<sup>-1</sup> respectively, with intensity ratio ( $I_{2D}/I_G$ ) of 2.21, as shown in Figure 2E. After transfer no obvious D bend (1350 cm<sup>-1</sup>) was observed in Figure 2F, indicating the no sp<sup>3</sup> defects were generated during the transfer in graphene.<sup>31,32</sup>

To better investigate the transfer effect of graphene on UHMWPE membrane, SEM and AFM were performed to observe the composite membrane surfaces (graphene on top of UHMWPE). Figure 3A shows graphene/UHMWPE composite membrane by new direct transfer method. It can be seen that the graphene was fully extended on UHMWPE without ripples or folds. While Figure 3B shows the transfer results by conventional PMMA-mediated method, micrometer level ripples and folds are obviously seen. If the ripples are millimeter sized, graphene will be tore-away during the removal of PMMA. Figure 3C and 3D are AFM height and peak force error images of

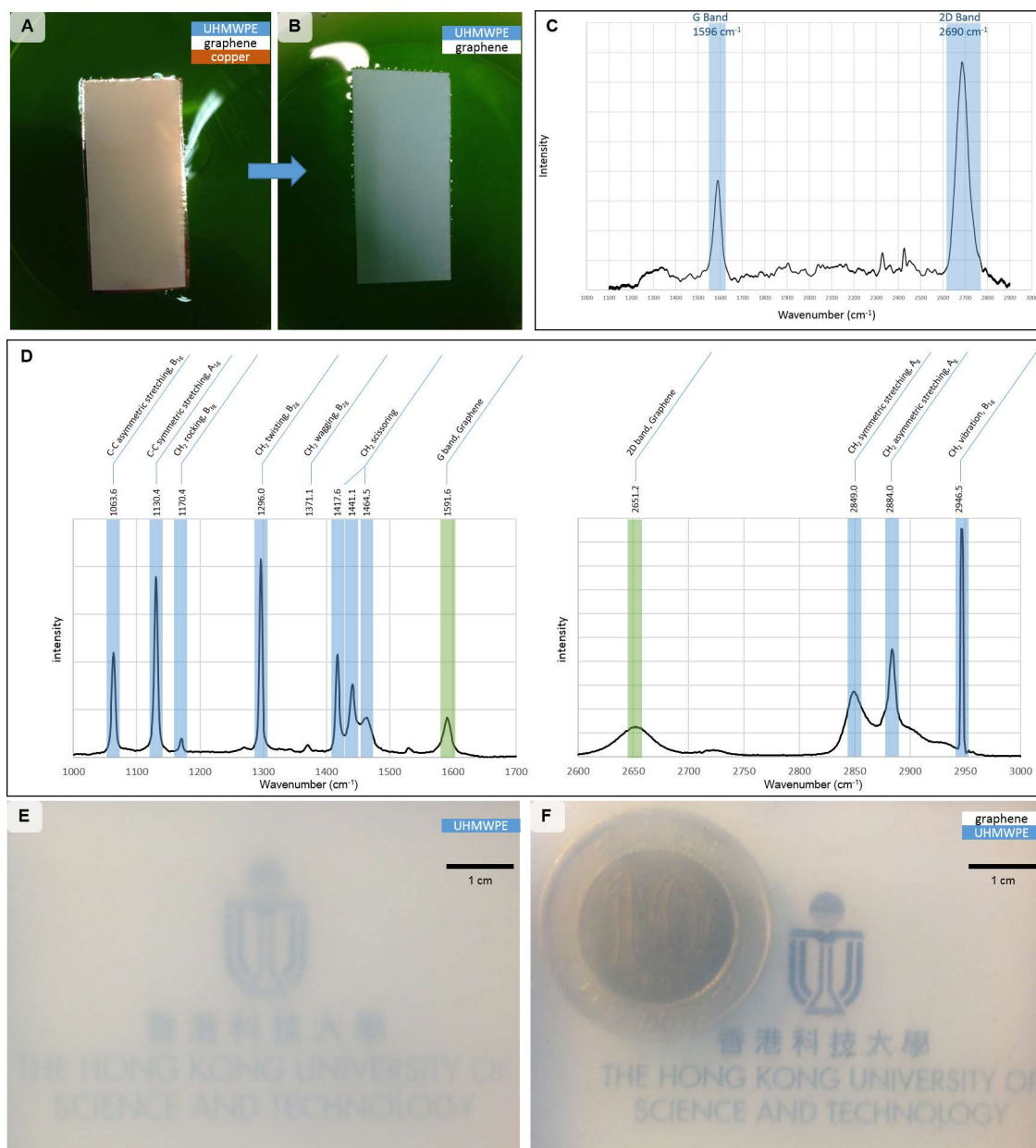


Figure 2: (A) Photograph of pure UHMWPE nano-porous membrane. (B) Photograph of UHMWPE/graphene composite membrane. (C-D) Photograph of UHMWPE/graphene composite membrane during and after copper etching. (E) Raman spectra of graphene on copper right after CVD grow. (F) Raman spectra of UHMWPE/graphene composite membrane, blue stripes indicate the peaks belong to UHMWPE, and green ones for those of graphene.

graphene/UHMWPE composite membrane surface, respectively. Graphene closely pressed itself against UHMWPE, thus it fitted the surface roughness of UHMWPE so well that the probe can still detect part of the contour of crisscrossed polymer chain superstructure. By more carefully investigating the height profile at cross-sections, the difference of with and without graphene covering become apparent. Figure 3E is the cross-sectional height profile taken from Figure 3C marked with a blue line. The upper parts (tops) of polymer chain structure can always be detected no matter with or without graphene covering. However the lower parts (bottoms) cannot be reached by probes because of the existence of graphene. Thus it can be concluded that: (1) graphene is closely stuck against UHMWPE surface by vdW force and fits the surface contour well, (2) graphene and UHMWPE are not closely contacted at each point, micro-chambers enclosed by graphene and relatively rough UHMWPE surface exist, (3) which is quite promising to be used to study intrinsic properties of graphene such as its mechanical properties.

One of the most considerable applications of graphene/UHMWPE composite membrane prepared by direct wet transfer method lies on that it developed a whole new approach to directly observe crystallization and phase behaviors of UHMWPE. These topics have been intensively studied for several decades, however the real time direct structural observation on sub-micron level has seldom been performed, especially for UHMWPE-solvent system. In situ AFM once was used to investigate the formation of shish-kebab structures of UHMWPE,<sup>33,34</sup> but due to the trade-off of scanning speed and resolution of AFM, the results were either not real-time or with not enough resolution. Our new direct wet transfer method may solve problem by utilizing graphene as both the conductive coating layer and the encapsulating material in case the solvent involved. As shown in Figure 4A, after coated with gold, graphene loaded on UHMWPE membrane was not transparent at all to SEM, since the electrons immediately dissipated upon reaching highly conductive gold coating layer, and also the gold coating was far thicker than graphene. But if no gold was coated, SEM could ‘see’ through graphene and observe UHMWPE directly (which is not possible for UHMWPE alone since it has quite low electrical conductivity), as shown in Figure 4B. This SEM micro-photograph is somewhat similar to those captured by AFM, as shown in Fig-



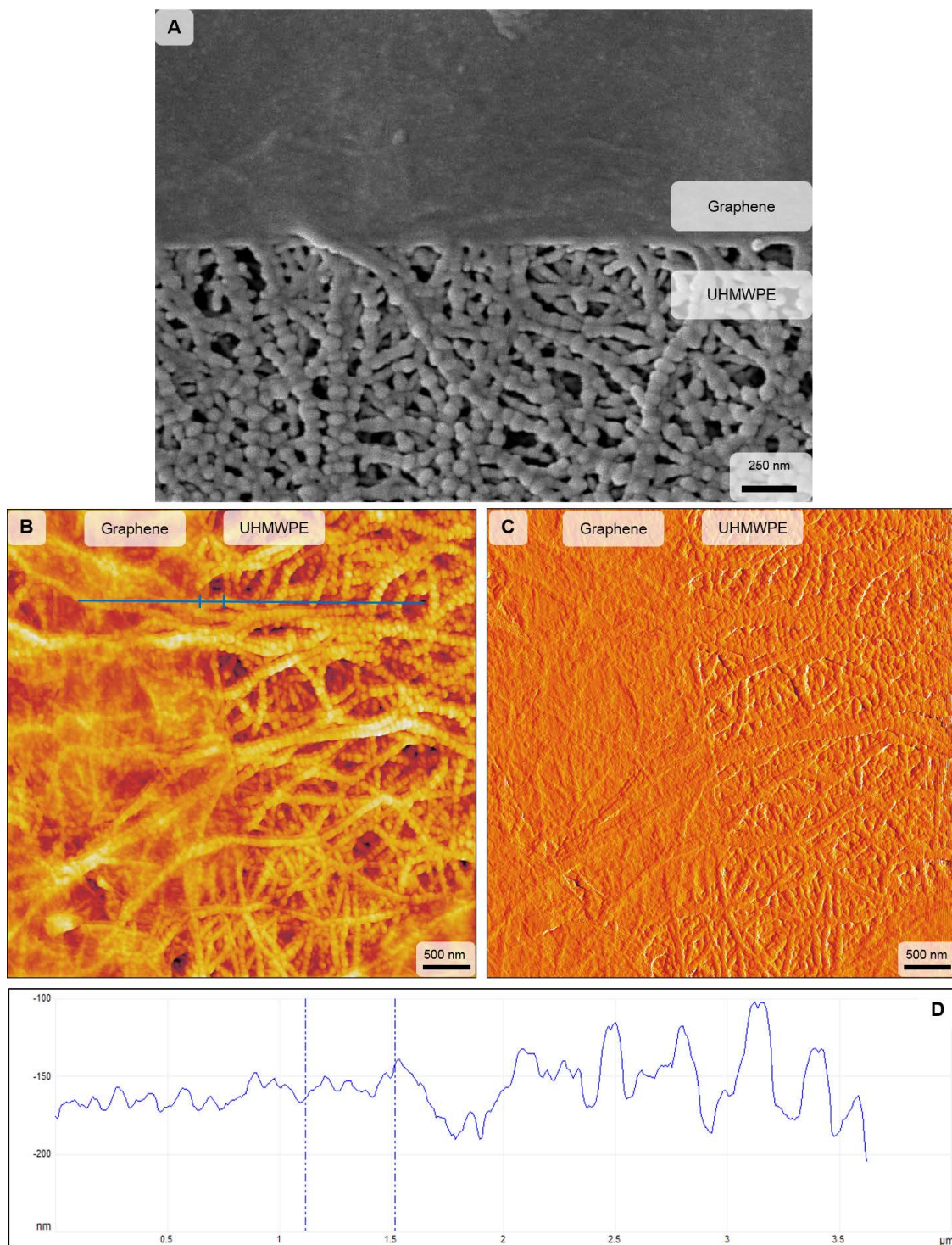


Figure 3: (A) SEM photograph of graphene on UHMWPE membrane, transferred by new direct wet transfer method. (B) SEM photograph of graphene on UHMWPE membrane, transferred by conventional PMMA-mediated method. (C, D) AFM height and peak force error image of graphene on UHMWPE membrane, transferred by new direct wet transfer method. (E) Cross-sectional height profile of region marked with blue line in (C).



ure 4C-D, they all showed the surface morphology and micro-structure of UHMWPE membrane through graphene, but with different mechanisms. AFM probe can “touch” UHMWPE through graphene because graphene is atomic-thin, highly flexible and closely stuck against UHMWPE by vdW force, thus the upper part of UHMWPE structure is easily capture by AFM. While SEM can “see” UHMWPE through graphene by simply conducting electron through is more impressive, since it implies the possibility of direct in situ electron microscopic observations (e.g., TEM) of crystallization process and phase behaviors of UHMWPE and even other polymers in the presence of its solvent and thermal treatment. The only obstacle seems to be the need to coat both sides of UHMWPE with graphene, which is also a huge challenge for conventional graphene transfer method.

Fortunately, this obstacle is not a problem to our new direct transfer approach and it has been solved. Due to the hydrophobic-hydrophobic interactions and strong vdW force between graphene and UHMWPE, they will not easily split up any more once stuck together, even though they are immersed into water or aqueous solutions again. Thus new direct wet transfer can be performed more than once, e.g., graphene/UHMWPE/graphene (graphene-encapsulated UHMWPE) and UHMWPE/graphene/UHMWPE (UHMWPE-encapsulated graphene) composite membranes were prepared by simply repeating this method to transfer extra layer of graphene or UHMWPE onto prepared graphene/UHMWPE membrane. In fact, the multi-layer sandwich structure 2D composite membrane can be prepared at ease with desired number of layers, as illustrated in Figure 5.

Preparation of polymeric composite materials consisting embedded graphene has been reported, while 2D layered composite membrane of one single layer large-area graphene and polymer is rarely studied.<sup>35,36</sup> By performing direct transfer approach, large-area layered graphene/UHMWPE composite membranes were prepared, with desired number of layers and layers arrangement. To better investigate the adhesion between graphene/UHMWPE and effect of existence of graphene on mechanical properties of UHMWPE, a series of stretching with assigned strains was performed. As shown in Figure 6, three groups of samples were demonstrated after stretching with strain of

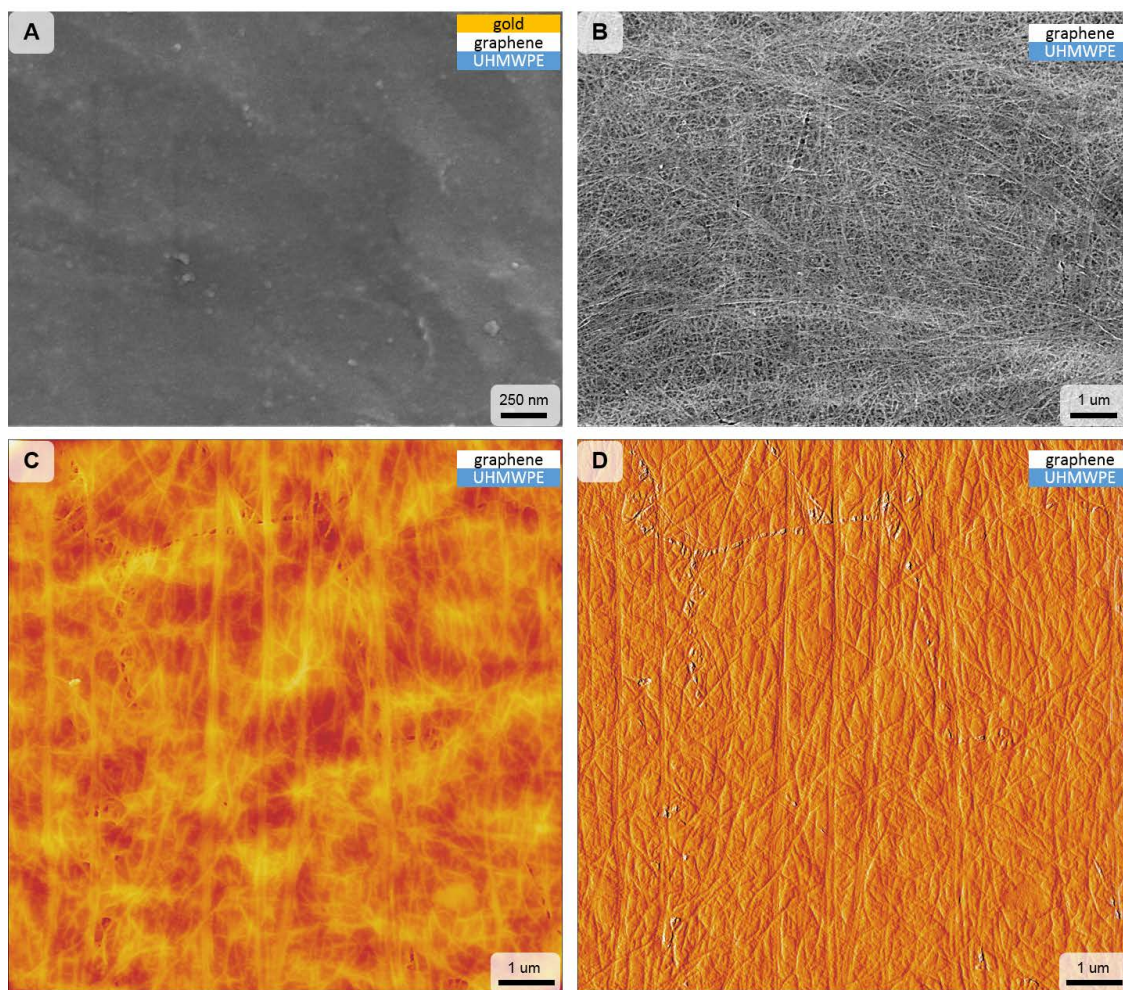


Figure 4: (A, B) SEM photographs of graphene/UHMWPE composite membrane prepared by new direct wet transfer method, with and without gold coating. (C, D) AFM height and peak force error images of graphene/ UHMWPE composite membrane prepared by new direct wet transfer method.

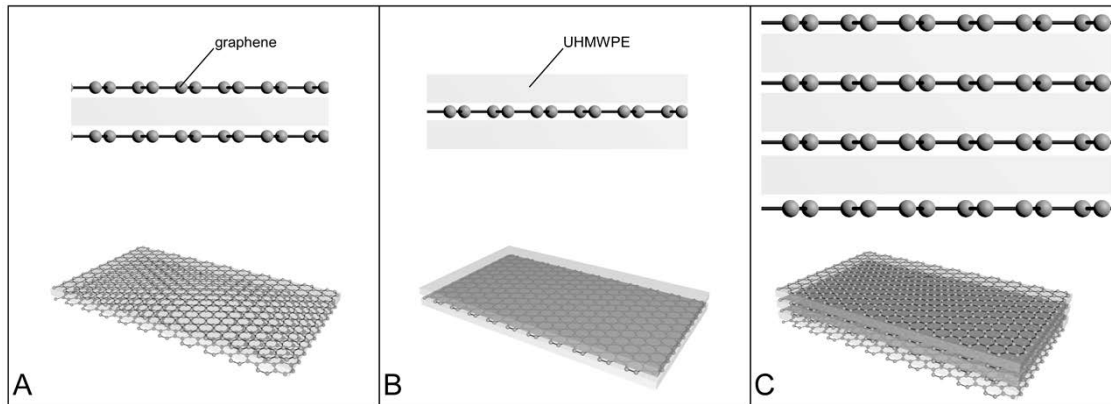


Figure 5: (A) Illustration of graphene-encapsulated UHMWPE membrane. (B) Illustration of UHMWPE-encapsulated graphene. (C) Illustration of multi-layer sandwich structure of graphene/UHMWPE 2D composite membranes.

20%, 50% and 80%, respectively. Figure 6A, B & C are SEM photographs of stretched pure UHMWPE membrane with gold coating, Figure 6D, E & F are SEM photographs of stretched graphene/UHMWPE composite membranes without gold coating, Figure 6G, H & I are AFM height images of stretched composite membranes. As draw ratio increases, UHMWPE originally biaxial chains became more oriented along stretching direction. Thus graphene above was tearing up by aligning UHMWPE, this would not occur except the strong adhesion existed between them two. Rifts of graphene are indicated with arrows, they appear brighter in SEM due to the electron charging effect at the edge of graphene fragments. With higher draw ratios, split graphene was pulled away from each other and even became isolated, and piled up normal to stretching direction on account of the Poisson effect. Exposed UHMWPE which lost the covering of graphene charged severely, and the structure details could be hardly distinguished. While with graphene fragments above (even rippled ones), chain orientation and shish-kebab structures could still be identified.

Table 1: Tensile properties of graphene/UHMWPE composite membranes

| Sample                   | Max. Stress, (MPa) | Young's Modulus, (MPa) | EAB(%)       | Fracture Energy (MPa) |
|--------------------------|--------------------|------------------------|--------------|-----------------------|
| UHMWPE                   | 111.9 $\pm$ 6.8    | 540.0 $\pm$ 39.7       | 97 $\pm$ 11  | 78.0 $\pm$ 5.1        |
| graphene/UHMWPE          | 130.7 $\pm$ 9.5    | 541.0 $\pm$ 43.2       | 105 $\pm$ 14 | 114.0 $\pm$ 8.3       |
| graphene/UHMWPE/graphene | 123.4 $\pm$ 8.5    | 514.8 $\pm$ 38.4       | 111 $\pm$ 13 | 126.3 $\pm$ 8.0       |

Cracks on stretched graphene on UHMWPE might stem from original defects, and did not overlap with possible domain boundaries of graphene (black contour in Figure 7A). Strengthening



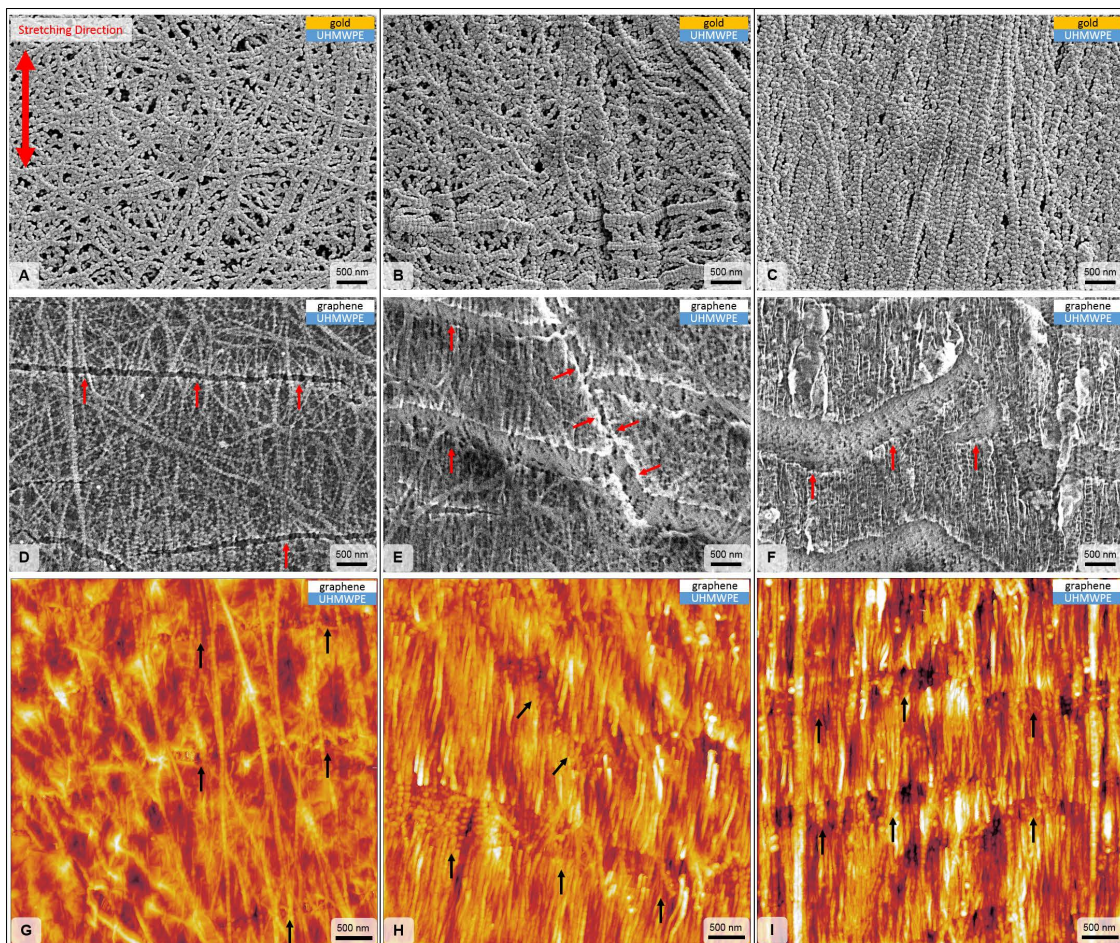


Figure 6: (A, B, C) SEM photographs of UHMWPE membranes stretched by 20%, 50% and 80%, respectively. (D, E, F) SEM photographs of graphene/UHMWPE composite membranes stretched by 20%, 50% and 80%, respectively. (G, H, I) AFM height images of graphene/UHMWPE composite membranes stretched by 20%, 50% and 80%, respectively.

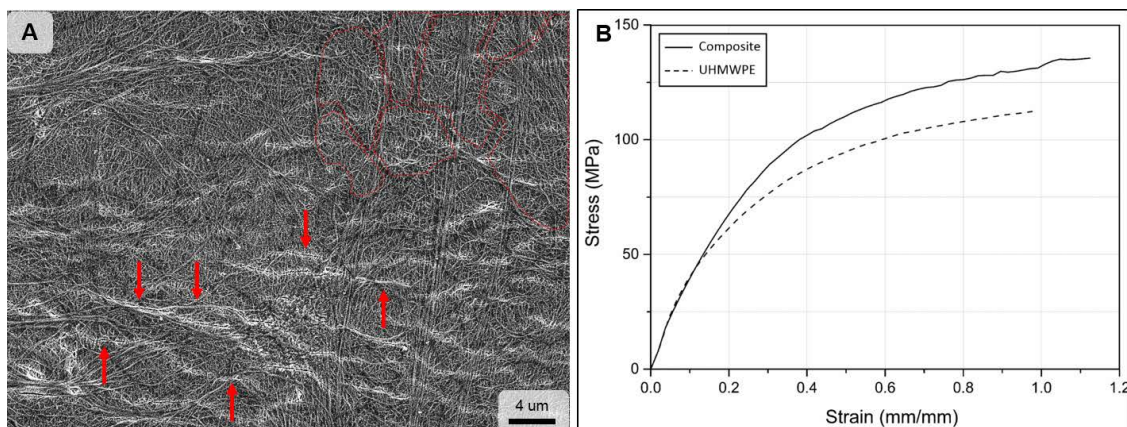


Figure 7: (A) Cracks and possible domain boundaries of stretched graphene on UHMWPE, arrows indicate the cracks while the dash line indicate the possible domain boundaries. (B) Stress-strain curves of graphene/UHMWPE/graphene, graphene/UHMWPE and UHMWPE membranes.

effect of graphene in graphene/UHMWPE layered composite membranes has been observed. With the covering of atomic-thin graphene on one side or both sides, UHMWPE would increase in maximum stress (16.8% and 10.3%), ductility (8.2% and 14.4%) and fracture energy (46.2% and 61.9%), as demonstrated in Figure 7B and Table 1.

## 4. Conclusions

It has been demonstrated that a new direct wet transfer method to transfer graphene onto arbitrary thin polymer membranes has been developed by harnessing hydrophobic-hydrophobic interactions between graphene and polymers. This method does not introduce any organic coating, thermal treatment or mediated substrate, thereby not only avoiding PMMA-residue and PMMA-induced cracking issues, but also being technically facile and economically preferable, especially for large-area graphene preparation. Furthermore, with this method multi-layer sandwich graphene/polymer composite membranes can be easily prepared, by repeating the method the stacking with desired number of layers can be achieved. And graphene encapsulated polymer membranes prepared by this method can be further applied for real time in situ electron microscopic observation of crystallization process and phase behaviors of polymer including UHMWPE, even in the presence

of their solvent and thermal control. Strengthening effect of atomic-thin graphene covering of UHMWPE was observed by investigating the stretching of graphene/UHMWPE layered composite membranes. Other important applications of prepared graphene/UHMWPE composite membranes include the investigation of intrinsic properties study of graphene. Super capacitor?

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## References

- (1) Bolotin, K. I.; Sikes, K.; Jiang, Z.; Klima, M.; Fudenberg, G.; Hone, J.; Kim, P.; Stormer, H. *Solid State Communications* **2008**, *146*, 351–355.
- (2) Bunch, J. S.; Verbridge, S. S.; Alden, J. S.; Van Der Zande, A. M.; Parpia, J. M.; Craighead, H. G.; McEuen, P. L. *Nano letters* **2008**, *8*, 2458–2462.
- (3) Lee, C.; Wei, X.; Kysar, J. W.; Hone, J. *science* **2008**, *321*, 385–388.
- (4) Lee, J.-U.; Yoon, D.; Cheong, H. *Nano letters* **2012**, *12*, 4444–4448.
- (5) Blake, P.; Hill, E.; Neto, A. C.; Novoselov, K.; Jiang, D.; Yang, R.; Booth, T.; Geim, A. *Applied Physics Letters* **2007**, *91*, 063124.
- (6) Geim, A. K. *science* **2009**, *324*, 1530–1534.
- (7) Novoselov, K. S.; Geim, A. K.; Morozov, S. V.; Jiang, D.; Zhang, Y.; Dubonos, S. V.; Grigorieva, I. V.; Firsov, A. A. *science* **2004**, *306*, 666–669.
- (8) Li, X.; Cai, W.; An, J.; Kim, S.; Nah, J.; Yang, D.; Piner, R.; Velamakanni, A.; Jung, I.; Tutuc, E. *Science* **2009**, *324*, 1312–1314.
- (9) Li, X.; Zhu, Y.; Cai, W.; Borysiak, M.; Han, B.; Chen, D.; Piner, R. D.; Colombo, L.; Ruoff, R. S. *Nano letters* **2009**, *9*, 4359–4363.
- (10) Reina, A.; Jia, X.; Ho, J.; Nezich, D.; Son, H.; Bulovic, V.; Dresselhaus, M. S.; Kong, J. *Nano letters* **2008**, *9*, 30–35.
- (11) Kang, J.; Shin, D.; Bae, S.; Hong, B. H. *Nanoscale* **2012**, *4*, 5527–5537.
- (12) Lin, Y.-C.; Jin, C.; Lee, J.-C.; Jen, S.-F.; Suenaga, K.; Chiu, P.-W. *ACS nano* **2011**, *5*, 2362–2368.



- (13) Pirkle, A.; Chan, J.; Venugopal, A.; Hinojos, D.; Magnuson, C.; McDonnell, S.; Colombo, L.; Vogel, E.; Ruoff, R.; Wallace, R. *Applied Physics Letters* **2011**, *99*, 122108.
- (14) Suk, J. W.; Lee, W. H.; Lee, J.; Chou, H.; Piner, R. D.; Hao, Y.; Akinwande, D.; Ruoff, R. S. *Nano letters* **2013**, *13*, 1462–1467.
- (15) Kim, K. S.; Zhao, Y.; Jang, H.; Lee, S. Y.; Kim, J. M.; Kim, K. S.; Ahn, J.-H.; Kim, P.; Choi, J.-Y.; Hong, B. H. *Nature* **2009**, *457*, 706–710.
- (16) Kang, J.; Hwang, S.; Kim, J. H.; Kim, M. H.; Ryu, J.; Seo, S. J.; Hong, B. H.; Kim, M. K.; Choi, J.-B. *ACS nano* **2012**, *6*, 5360–5365.
- (17) Lin, W.-H.; Chen, T.-H.; Chang, J.-K.; Taur, J.-I.; Lo, Y.-Y.; Lee, W.-L.; Chang, C.-S.; Su, W.-B.; Wu, C.-I. *ACS nano* **2014**, *8*, 1784–1791.
- (18) Song, J.; Kam, F.-Y.; Png, R.-Q.; Seah, W.-L.; Zhuo, J.-M.; Lim, G.-K.; Ho, P. K.; Chua, L.-L. *Nature nanotechnology* **2013**, *8*, 356–362.
- (19) Chen, X.-D.; Liu, Z.-B.; Zheng, C.-Y.; Xing, F.; Yan, X.-Q.; Chen, Y.; Tian, J.-G. *Carbon* **2013**, *56*, 271–278.
- (20) Regan, W.; Alem, N.; Alemán, B.; Geng, B.; Girit, Ç.; Maserati, L.; Wang, F.; Crommie, M.; Zettl, A. *Applied Physics Letters* **2010**, *96*, 113102.
- (21) Wang, B.; Huang, M.; Tao, L.; Lee, S. H.; Jang, A.-R.; Li, B.-W.; Shin, H. S.; Akinwande, D.; Ruoff, R. S. *ACS nano* **2016**, *10*, 1404–1410.
- (22) Wang, D.-Y.; Huang, I.; Ho, P.-H.; Li, S.-S.; Yeh, Y.-C.; Wang, D.-W.; Chen, W.-L.; Lee, Y.-Y.; Chang, Y.-M.; Chen, C.-C. *Advanced Materials* **2013**, *25*, 4521–4526.
- (23) Na, S. R.; Suk, J. W.; Tao, L.; Akinwande, D.; Ruoff, R. S.; Huang, R.; Liechti, K. M. *ACS nano* **2015**, *9*, 1325–1335.

- (24) Yoon, T.; Shin, W. C.; Kim, T. Y.; Mun, J. H.; Kim, T.-S.; Cho, B. J. *Nano letters* **2012**, *12*, 1448–1452.
- (25) Lin, Y.-C.; Lu, C.-C.; Yeh, C.-H.; Jin, C.; Suenaga, K.; Chiu, P.-W. *Nano letters* **2011**, *12*, 414–419.
- (26) Gibb, B. C. *Chemosensors: Principles, Strategies, and Applications* **2011**, 3–18.
- (27) Hermans, J.; Lentz, B. *Equilibria and kinetics of biological macromolecules*; John Wiley & Sons, 2013.
- (28) Mie, G. *Annalen der physik* **1908**, *330*, 377–445.
- (29) Yabu, H.; Shimomura, M. *Chemistry of materials* **2005**, *17*, 5231–5234.
- (30) Kaplan, I. G. *Intermolecular interactions: physical picture, computational methods and model potentials*; John Wiley & Sons, 2006.
- (31) Ferrari, A.; Meyer, J.; Scardaci, V.; Casiraghi, C.; Lazzeri, M.; Mauri, F.; Piscanec, S.; Jiang, D.; Novoselov, K.; Roth, S. *Physical review letters* **2006**, *97*, 187401.
- (32) Ferrari, A. C. *Solid state communications* **2007**, *143*, 47–57.
- (33) Hobbs, J.; Humphris, A.; Miles, M. *Macromolecules* **2001**, *34*, 5508–5519.
- (34) Hobbs, J.; Miles, M. *Macromolecules* **2001**, *34*, 353–355.
- (35) Liu, A.; Li, C.; Bai, H.; Shi, G. *The Journal of Physical Chemistry C* **2010**, *114*, 22783–22789.
- (36) Zhang, H.; Bao, Q.; Tang, D.; Zhao, L.; Loh, K. *Applied Physics Letters* **2009**, *95*, 141103.